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MEASUREMENT-COMPUTER SYSTEM BASED ON AIRBORNE HYPERSPECTROMETER

This paper focuses on a new methodology and a measurement-computer system for detection of biological and chemical agents including various toxins and viruses. A new methods and algorithms are presented, which are feasible for cooperative execution of complex tasks by multiple autonomous unmanned vehicles (both aerial (UAV) and ground (UGV)) during intricate missions. A nonlinear dynamic system with many attractors in phase space for the classification of spectral data is considered. A signal processing of spectral data for remote detection of chemical and biological agents is presented. A novel concept of a compact integrated spectrometer for environmental monitoring of chemical and biological agents as well as for remote monitoring of vegetation is discussed.

Keywords: measurement-computer system, chemical and biological agents, dynamic model, pattern recognition, autonomous unmanned vehicle.

1 Introduction

The ecological interest is in response to a proliferation of agents development and threats for human health. Additionally, there is a pervasive interest across diverse application areas such as medicine, environmental protection, and vegetation monitoring to achieve a rapid detection and identification capability of various agents. In many cases, a standoff capability is desired. Technologies such as optical spectroscopy measurements, laser induced fluorescence, pattern recognition and optimization methods are used in our device [1; 2]. This device is intended to be used for ground measurements or can be installed on small airplanes for remote sensing. In this paper we concentrates on environmental dynamic probabilistic risk assessment with complex characterizations of hazards using physical models and predictable level of biological and chemical agents [3; 4].

The hyperspectral imaging is an advanced facility for detecting ground pollutants [5]. Optical spectra of the Earth's surface objects depends on chemical and biological pollutants. Unique property of hyperspectral imaging is the ability to capture fine spectral differences in optical spectra and thus identify the anthropogenic pollution. The primary targets for remote detection of chemical and biological pollutants are vegetation and open soil [6].

Remote sensing of chemical and biological agents through hyperspectral sensors and analysis remains dependent on current sensors and algorithms. With the advent of both airborne and spaceborne hyperspectral systems, government agencies have had the opportunity to assess the utility of hyperspectral technology for detection and identification applications. The ground-based and airborne sensors are increasingly involved for hyperspectral imaging.

2 Architecture

For the vegetation, soil and other objects of spectral measurement the two-channel field spectrometer is designed and manufactured in Ukraine. It consists of miniature optical unit, folding tripod, notebook, and data processing software. Optical unit contains a polychromator with flat diffraction grating, spherical mirror and CCD sensor. Technical specification of the field spectrometer is presented in Table 1.

Table 1. **Technical specification of the field spectrometer**

Specification	Value
Spectral range, nm	190 – 1100
Spectral resolution, nm	0.8 – 1.6
Time of exposition, msec	7.4
Analog-to-digital converter, bit	12
Weight, kg	0.9

On the basis of this instrument is planned to develop an onboard hyperspectrometer. It will be installed on an autonomous unmanned vehicle, both airborne and ground-based. This device will be apply for missions, such as rapid detection and localization of targets with chemical and biological agents inside large areas. It is assumed that the unmanned vehicle, besides hyperspectrometer, will be additionally equipped with digital imaging cameras of visible and infrared bands. The operator at any time will be able to obtain visual information on the mission progress.

We propose to use the Model Driven Architecture (MDA) for chemical and biological agents detection [7; 8]. The MDA approach is often referred to a model-centric approach as it focuses on the business logic rather than on implementation techniques of the system in a particular programming environment. This separation allows both business knowledge and technology to continue to develop without necessitating a complete rework of existing systems [7]. MDA uses the Unified Modeling Language (UML) to construct visual representations of hyperspectral device models. UML is an industry standard for visualizing, specifying, constructing, and documenting the artifacts of a software system [8].

However, reliable detection of chemical and biological agents by spectral measurements is very difficult. Sophisticated models for statistical analysis of field spectral measurements are developed for this purpose. Traditionally the spectral reflectivity of plants or derived various vegetation indices are used [8]. At later time the approach which is based on a quantitative attributes of the spectrum shape, was offered [8].

The main difficulties encountered during the data field spectrometry are:

- spectral variations caused by different environmental noise and internal noise;
- instability conditions, weather, etc.;
- small fraction of the target in scene objects;
- incomplete projective cover of surveyed objects on the ground, resulting in registration of mixture background spectra.

Additional complications arise when the sensor is mounted on the airborne platform:

- the impact of negative factors of flight are: the platform own motion, mechanical perturbations and vibrations;
- optical signals distortion while passing through the atmosphere;
- significant reduction in imaging spatial resolution, and, accordingly, more decrease of the target spectrum fraction in mixture.

So, the development a new conception to determine the contents of chemical and biological agents using spectral measurements is required. We proposed a model that based on a dynamic approach [6]. For reconstruction the field and laboratory spectral data has been obtained. The data was saved and used for the next investigations.

The first stage of data processing is a filtering because spectral measurements are always noisy. Two digital filters were used for the noise filtration: Savitzky-Golay filter and Butterworth filter. Results of field spectral data filtering are presented in Fig. 1.

The next stage is an informative feature selection, because the computational costs unacceptably heavy to process several thousands or tens of thousands of spectral samples that produce modern high-

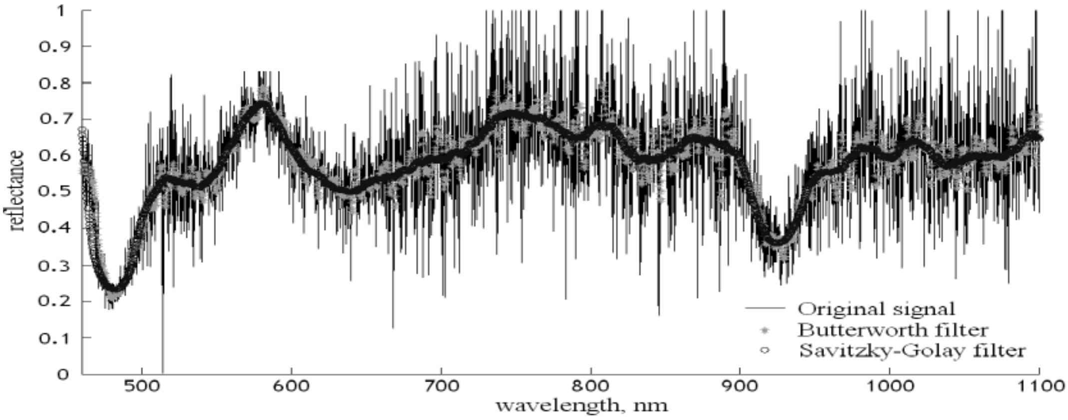

Fig. 1. Field reflectance spectra after filtering

precision spectrometers. In addition, the perfect feature extraction in addition to reducing the input data dimensionality can provide a significant increase in relevant information content.

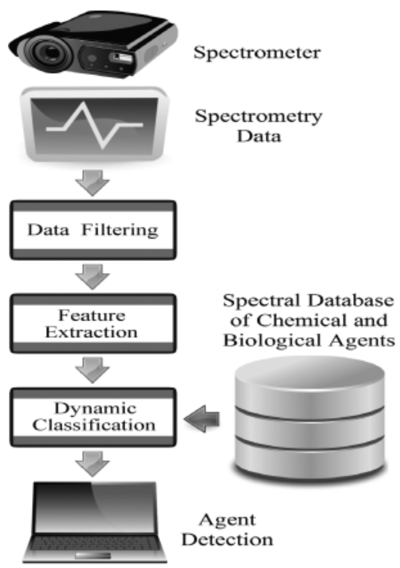

Fig. 2. Dataflow diagram of spectral data processing

Finally, the chemical and biological agents detection is performed by dynamic models and data processing of remote spectrometry. The overall processing sequence is described by the diagram (Fig. 2).

3 Mathematical Model

Let we discuss the problem of a dynamic classification of spectral curves $S_j(\lambda)$, $j \in J$ using the most informative characteristics of the reflectance spectra. We describe patterns by N-dimensional vector $\mathbf{y}$, whose individual components represents the most informative characteristics of the typical reflectance spectra of the the patterns.

$$\mathbf{y}_k = \begin{pmatrix} y_{1k} \\ \vdots \\ y_{Nk} \end{pmatrix}, \tag{1}$$

where $k = 1, ..., K$. Each pattern characterizes vegetation, soil or other objects states.

The solution of the problem is based on the following performances: 1) the most informative characteristics; 2) the dynamic system with many attractors; 3) the classification algorithm.

Let assume that the most informative characteristics $\mathbf{x}(t) = [x_1(t), x_2(t), \ldots, x_N(t)]^T$ have been estimated. Here T is the operation of transposition. Let us describe the pattern by the vector $\mathbf{x}(0)$, where 0 refers to the initial time $t = 0$ of the pattern recognition process. Then we describe the equation for the vector $\mathbf{x}(t)$. It is moved from the initial state $\mathbf{x}(0)$ into a final state that agrees with some prototype vector $\mathbf{y}_k$. The equations will be constructed in such a way that specific vector $\mathbf{y}_k$ is precisely the one, to which $\mathbf{x}(0)$ comes closest, i.e. for which $(\mathbf{y}_k \cdot \mathbf{x}(0))/(|\mathbf{y}_k| \cdot |\mathbf{x}(0)|)$ had the smallest value.

We assume

$$(\mathbf{y}_k^T \cdot \mathbf{y}_k) = \delta_{kk'}. \tag{2}$$

Generally the dynamic system for vegetation state estimation can be performed as

$$\frac{d\mathbf{x}}{dt} = \mathbf{F}(\mathbf{x}, \alpha) + \mathbf{G}(t), \tag{3}$$

where $\mathbf{F}(\cdot)$ – nonlinear function, α – control parameter, $\mathbf{G}(\cdot)$ – fluctuation force. Let dynamic system (3) has several attractors K each of them is characterized by the vector $\mathbf{y}_k$. Let present the equation (3) as

$$\dot{\mathbf{x}} = -\mathrm{grad}_x\, \mathbf{W} + \mathbf{G}(t), \tag{4}$$

where $\mathbf{W}$ is potential function, that is given by

$$\mathbf{W}(\mathbf{x}) = \mathbf{W}_0 + \mathbf{W}_1 + \mathbf{W}_2, \tag{5}$$

$$\mathbf{W}_0 = -\frac{1}{2}\mathbf{x}^T \sum_k \alpha\, \mathbf{y}_k \cdot (\mathbf{y}_k^T \cdot \mathbf{x}), \tag{6}$$

$$\mathbf{W}_1 = \sum_{k \neq k'} \mu_{kk'} (\mathbf{y}_k^T \cdot \mathbf{x})^2 (\mathbf{y}_{k'}^T \cdot \mathbf{x})^2, \tag{7}$$

$$\mathbf{W}_2 = \beta\, (\mathbf{x}^T \mathbf{x})^2, \tag{8}$$

$\alpha > 0$, $\mu_{kk'} > 0$, $\beta > 0$. $\mathbf{W}_0$ serves to pull $\mathbf{x}$ into the subspace spanned by the patterns. In the case of non-equilibrium phase transitions, this is simply the order parameter space. $\mathbf{W}_1$ serves for the discrimination of $\mathbf{x}$-vectors within that subspace. This can be easily seen from the property that the minimum of the $\mathbf{W}_1$ is adopted according to

$$\mathbf{W}_{1,\min} = 0 \text{ for } \mathbf{x} \| \mathbf{y}_k, \quad (9)$$

i. e. when the state vector becomes parallel to one of the patterns vectors and thus the initial state vector $\mathbf{x}(0)$ is identified with such a pattern. $\mathbf{W}_2$ provides for saturation, i.e. $|\mathbf{x}|$ is eventually pulled into a fixed point attractor on the $\mathbf{y}_{k0}$ axis. The constant α in (6) plays the role of a control parameter. Parameter $\alpha < 0$ determines the region below "threshold", whereas $\alpha > 0$ determines the region above "threshold". We also assume that $\alpha > 0$.

In order that $\mathbf{x}$ is more easily pushed into one of the patterns vectors, we have added a fluctuating force $\mathbf{G}$ in (4). As usual we assume that the fluctuating forces have the properties

$$\langle \mathbf{G}(t) \rangle = 0, \quad (10)$$

$$\langle \mathbf{G}_k(t)\, \mathbf{G}_{k'}(t') \rangle = C\delta_{kk'}\delta(t-t'), \quad (11)$$

where C is a constant; $\mathbf{G}(t)$ is a residual vector. The dynamical system (3) is able to perform the task of associative reconstruction of an input pattern to one of previously stored prototype patterns.

4 Conclusions and discussions

A new hybrid methodology for detection of biological and chemical agents has been proposed. The proposed methodology is based on pattern recognition and optimization techniques. We have shown that the idea and methods of nonlinear dynamics which are applied successfully in the investigation of pattern formation in systems far from thermal equilibrium has the fundamental importance in biological and chemical agents recognition.

We shown that vegetation in the path of filaments induced by intense femtosecond laser pulse propagating in air could be fragmented and result in the emission of characteristic fluorescence spectra from the excited fragments. The fluorescence spectra exibit specific signature that can be used for the identification of chemical and biological agents.

A new methodology and algorithms are feasible for cooperative execution of complex tasks by multiple autonomous unmanned vehicles (both aerial and ground during intricate missions). The UAV provide a platform for developing new sensors and techniques for earlier detecting biological and chemical agents.

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ВИМІРЮВАЛЬНО-ОБЧИСЛЮВАЛЬНА СИСТЕМА НА ОСНОВІ АВІАЦІЙНОГО ГІПЕРСПЕКТРОМЕТРА

Статтю присвячено новій методології та вимірювально-обчислювальній системі для виявлення біологічних і хімічних речовин, у тім числі різні токсини та віруси. Представлено нові методи та алгоритми, які дають змогу вести кооперативний пошук складних об'єктів за допомогою кількох автономних безпілотних літальних апаратів (повітряних (ПБЛА) і наземних (НБЛА)) під час пошукових місій. Розглянуто нелінійні динамічні системи з багатьма атракторами в фазовому просторі для класифікації спектральних даних. Представлено методи цифрової обробки спектральних даних для дистанційного виявлення хімічних і біологічних агентів. Обговорено концепцію малогабаритних спектрометрів для екологічного моніторингу хімічних і біологічних агентів, а також для дистанційного моніторингу стану рослинності.

Ключові слова: вимірювально-обчислювальна система, хімічні і біологічні агенти, динамічна модель, розпізнавання образів, безпілотний засіб.

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